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Application of a Portable F-Scan System

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Executive Summary

Recent advances in biomechanics have the potential to assist in the reduction of overuse injuries in the military. The three major components for this effort are: 1) a predictive overuse injury model, 2) a *portable* sensor to measure the primary input of the model—ground reaction forces, and 3) analysis of data from personnel undergoing military field exercises. This work evaluates a prototype portable sensor modified from an F-scan system. The accuracy of the F-scan system to measure ground reaction forces has been addressed in a previous report (Sih 2001).

The F-scan system (Tekscan, Inc., Boston, MA) is an in-shoe sensor that measures plantar pressure distribution using a thin disposable sheet composed of an array of pressure sensing elements or *sensels*. Currently, the F-scan system is "tethered" to a PC-compatible computer with 10-meter cables. The portable system developed by Jaycor, Inc. is designed to temporarily store F-scan sensor output in a transportable memory system, which can be downloaded to a computer at a later time. The current prototype can collect 4000 frames of data from each foot.

To demonstrate the capabilities of the portable system, plantar pressure data was collected from a subject performing a variety of movements that would have been impractical or impossible to measure using a nonportable system. In addition, a few analyses were completed to show the range of information available from the system. Specifically, walking and running was recorded outside on different terrains. These included level ground, both up and down a slope and on stairs. Step rate, stance time, total load and loads on different regions of the foot were calculated from the data. Significant differences were seen in the measurements depending on the terrain. A demonstration movie has been included on a CD.

The portable F-scan system was able to collect plantar pressure data from a set of conditions that are not typically analyzed using traditional biomechanic methods, allowing an analysis under different terrains and gait speeds. Such information may be valuable for many studies, including overuse injuries. The next step should be to increase the memory capacity and decrease the size/weight specifications of the system to allow longer data collection times with a smaller impact on the subject.

Introduction

One of the limitations of the F-scan system is the inability of the sensors to record data outside the laboratory. Currently, the F-scan system is "tethered" to a PC-compatible computer with 10-meter cables. Therefore, it is unable to record movements that extend beyond this range such as hills or stairs. This report describes a *portable* F-scan system, developed by Jaycor, Inc., to address this limitation.

The F-scan system (Tekscan, Inc., Boston, MA) is an in-shoe sensor that measures plantar pressure distribution using a thin disposable sheet composed of an array of pressure sensing elements or *sensels*. Patented ink within each sensel changes electrical resistance with load and a PC-based hardware and software package (currently at version 4.46) monitors the sensels, using a calibration scheme to convert the electrical resistance to pressure. The F-scan A/D converter has a resolution of two bytes that can distinguish 256 levels of pressure. For convenience, this "raw" sensel data is referred to as *TekUnits*. With a sensel area of 25.8 mm^2, up to 954 sensels can be placed in a shoe, depending on foot size. In addition, the system is capable of collecting plantar pressure data up to 169 Hz. The accuracy of the F-scan system has been addressed in a previous report (Sih 2001).

The portable system is designed to temporarily store left and right shoe F-scan sensor output in a transportable memory system, which can be downloaded to a computer at a later time. The current system can store 4096 frames of data per foot, enough for 40 seconds of data when sampling at 100 Hz. The unit is approximately 180 × 206 × 64 mm, weighs 2.3 kg with batteries, and fits comfortably in a hip-type pack (Figure 1). No processing of the data (e.g.,calibration, summing, etc.) is performed by the currently developed portable system. Only the raw TekUnits are stored before being downloaded to a computer for processing.

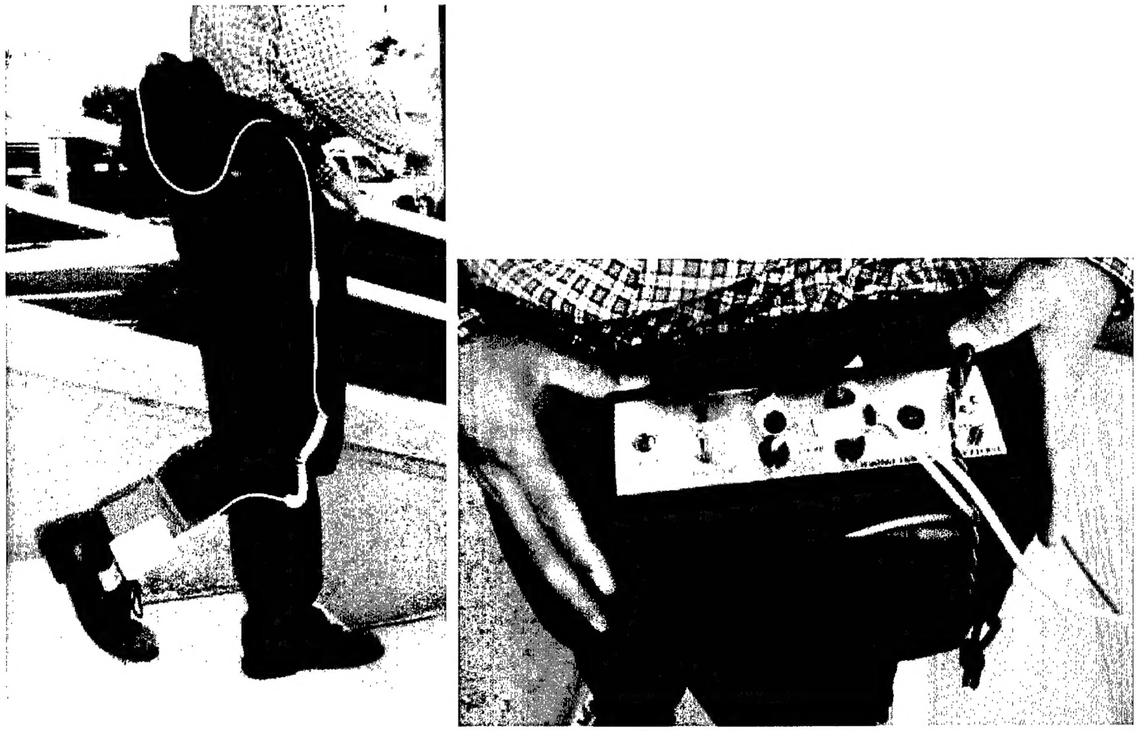

Figure 1. The portable F-scan system developed by Jaycor, Inc. The left picture shows the storage unit in the hip pack collecting data from a sensor inserted in the right shoe. The control panel allows data to be collected and downloaded easily (right picture). The portable system can collect from a left and right shoe sensor simultaneously.

Methods

To demonstrate the capabilities of the portable F-scan system, plantar pressure data was collected from a subject performing a variety of movements that would have been impractical or impossible to measure using a nonportable system. Walking and running was recorded outside on different terrains. These included level ground, both up and down a slope and on stairs. TekUnit data was collected at 100 Hz and downloaded to a computer for post-processing. A video camera recorded the subject's movement to coincide with the F-scan data.

A few analyses were completed to show the range of information available from the system. Gait parameters (step rate and stance time) were acquired from the saved F-scan data by recording the time each foot was in contact with the ground. In addition, total load in TekUnits was calculated by summing an entire sensor's output at each time step. For the walking trials (level and slope walking), peak total loads at early- and late-stance as well as the minimum load during mid-stance for each step were recorded. A single peak total load was recorded for the running trials. The pressure distribution pattern also allowed an analysis of different regions of the foot. Fore- and rear-foot peak pressures (i.e., toe and heel regions) for walking were calculated to demonstrate this feature.

To compare quantities, the results were normalized to values seen during normal walking or running. Significant differences between the gait speeds and terrain slopes were identified using an ANOVA with Tukey's HSD post-hoc comparisons.

Results

The portable system was able to record plantar pressure distributions for a wide range of terrain and gait speeds (e.g., Figure 2). This resulted in a total load profile that varied for each condition (Figure 3), allowing a wide range of analyses. The results from a few sample investigations are given below and a movie of some of the movements and results has been included on a CD. For example, the step rate for normal walking and running was 75 and 126 steps/min, respectively. Also, the amount of time the foot is in contact with the ground or stance time varied with gait speed and terrain. As expected, stance time for walking was greater than running (646±9 versus 187±5 msec). In addition, running up and down stairs as well as running uphill required longer stance times compared to running on level terrain and downhill ($p < 0.05$, Figure 4). As shown in Figure 5, peak forces while running were significantly higher running downhill (109±12% of normal running peak forces) compared to uphill (94±3%, $p < 0.05$).

Walking also showed significant changes depending on terrain. For example, forces while walking downhill tended to be higher during early-stance and lower during late-stance, the opposite of what was observed during uphill walking (Figure 6). This trend was further analyzed by looking at the pressure distribution in the fore- and rear-foot. During uphill walking, peak load on the forefoot was 126±5% of normal and 87±4% on the rear-foot region. However, downhill walking showed peak load on the forefoot of only 72±2% but an increased rear-foot load (121±9%). This can be most easily seen in Figure 7.

Figure 2. A subject demonstrating the portable F-scan system in grass.

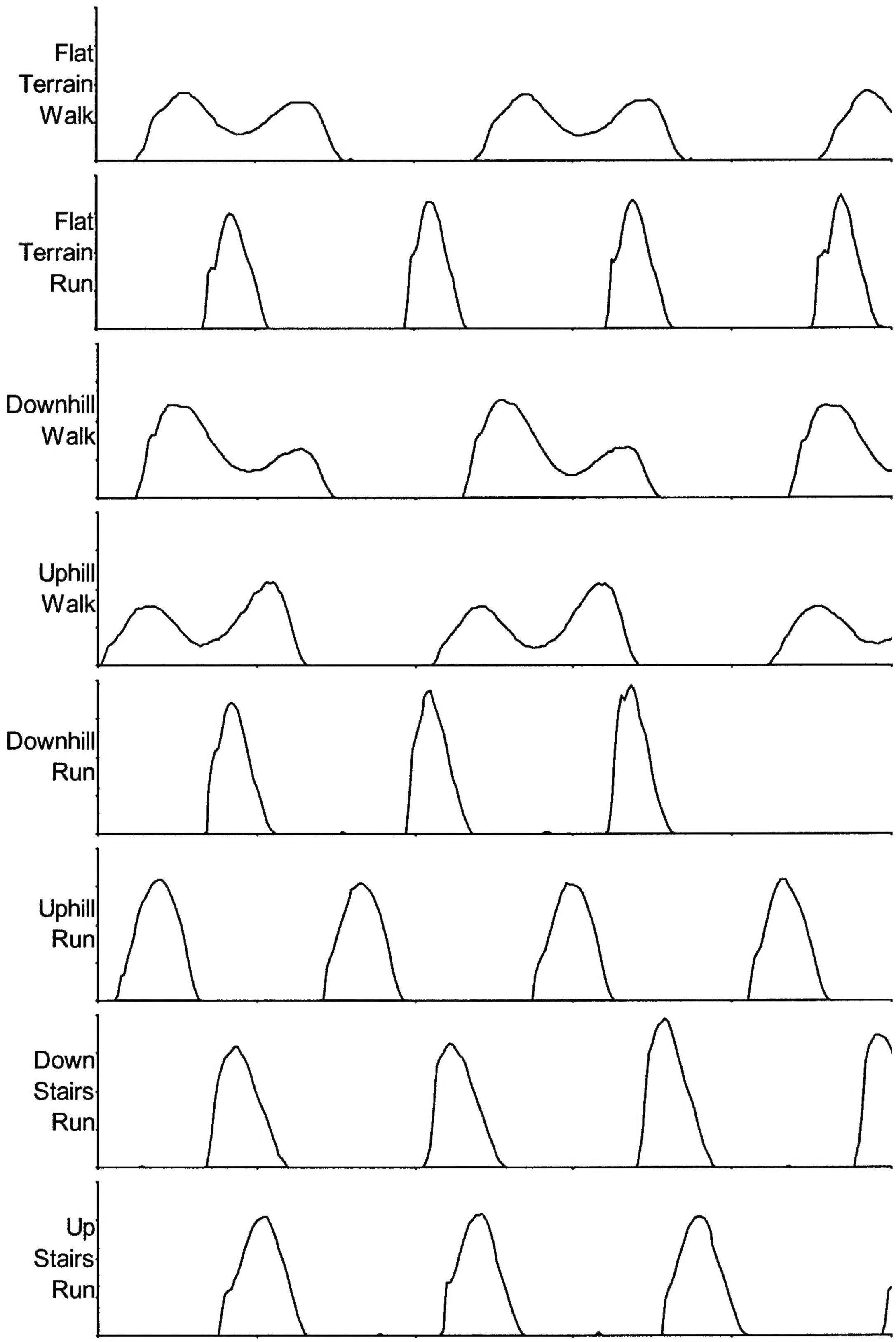

Figure 3. Total sensor output from the left shoe versus time during a variety of gait speeds and conditions.

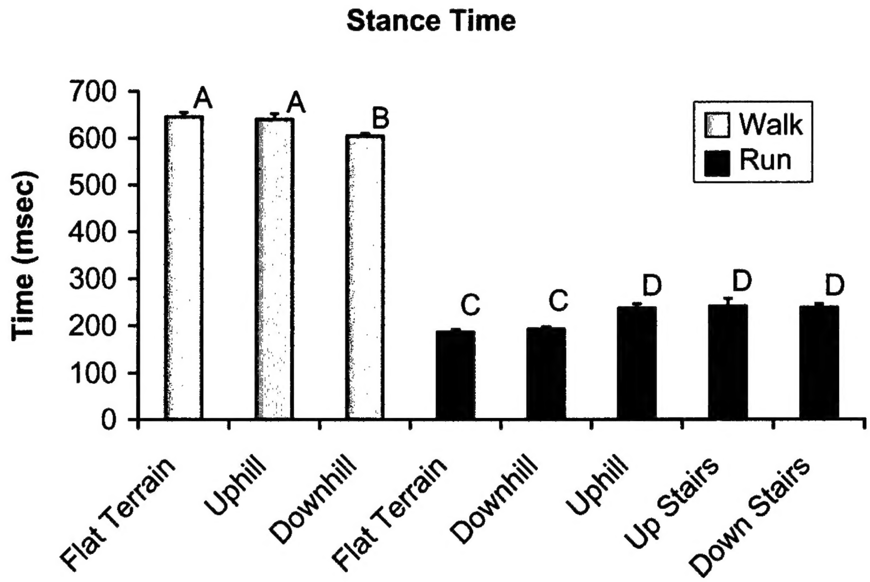

Figure 4. Stance time in msec (time when foot is in contact with the ground) for two gait speeds and five different terrains. Statistically significant differences between terrains are marked with the letters *A* through *D* ($p < 0.05$).

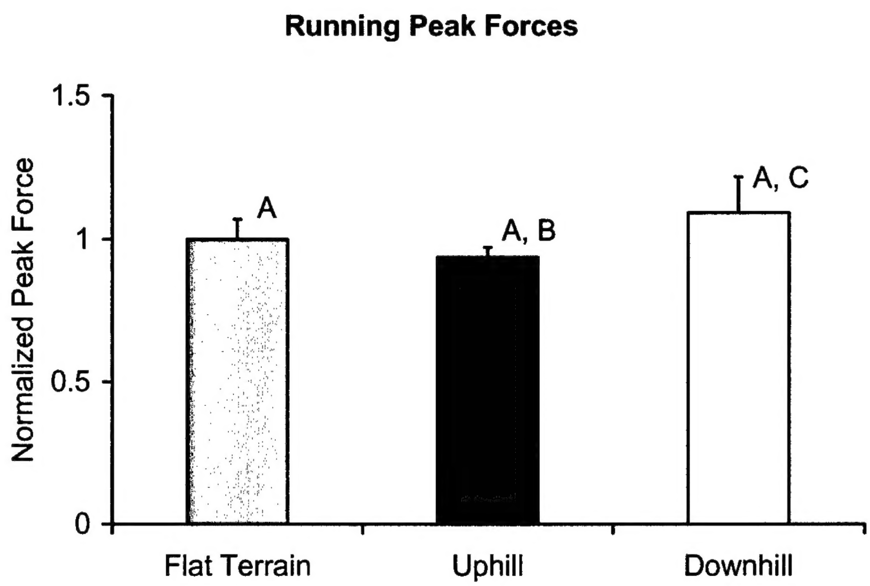

Figure 5. Running peak force normalized to flat terrain peak force. Statistically significant differences between terrains are marked with the letters *A*, *B* and *C* ($p < 0.05$).

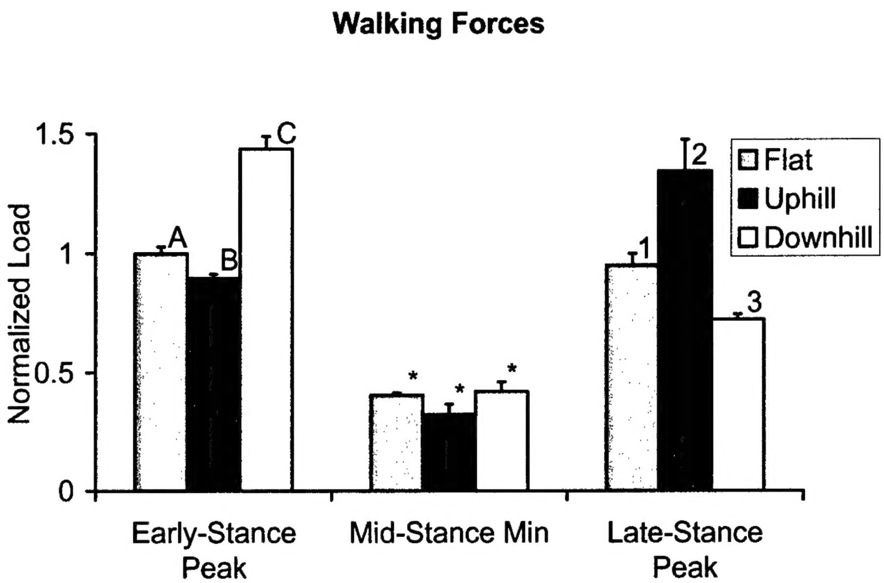

Figure 6. Peak forces at early-stance and late-stance with minimum forces during mid-stance for flat terrain, uphill and downhill walking. Forces were normalized to peak forces at early-stance for flat terrain. Differences between terrains were significant for early- and late-stance ($p < 0.001$) but not mid-stance.

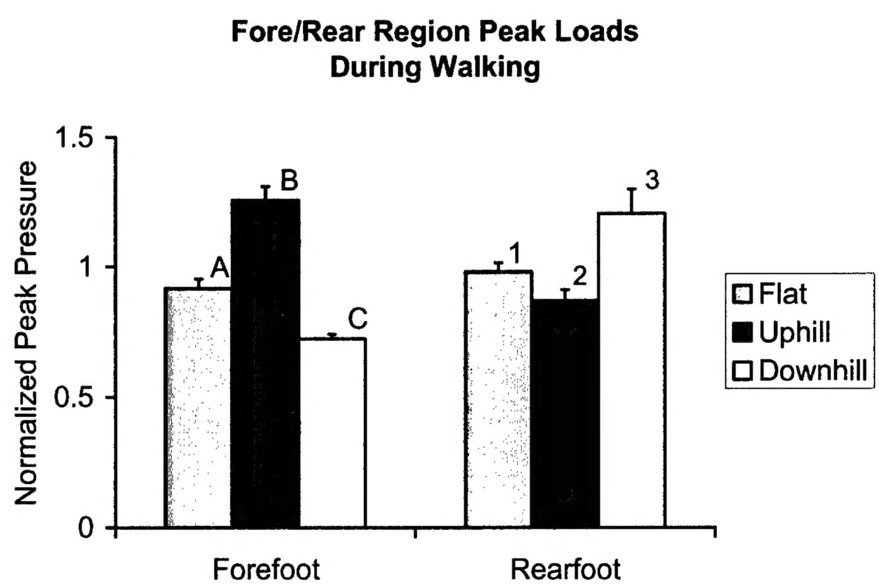

Figure 7. Peak forces on the forefoot and rear-foot during walking on flat terrain, uphill and downhill. Forces were normalized to peak forces at early-stance for flat terrain. Differences between terrains were significant ($p < 0.001$) for both the forefoot and rear-foot regions.

Discussion

The portable F-scan system was able to collect plantar pressure data from a set of conditions that are not typically analyzed using traditional biomechanic methods, allowing an analysis under different terrains and gait speeds. Such information may be valuable for many studies, including overuse injuries. For example, in the brief analysis described here, both uphill and downhill walking showed increased forces compared to level ground walking. However, the pressure distribution showed that the increased forces during downhill walking occur during early-stance, in the rear-foot or heel region. Thus, it is likely that this type of exercise would put additional strain (and presumably cause more damage) to the calcaneous, a region known to have overuse injuries (Kowal 1980). In addition, the added forces in the forefoot area due to extended uphill running may fatigue the muscles of the foot, putting additional strain on the metatarsal bones as they bear more tensile load (Donahue and Sharkey 1999).

Another area where the portable F-scan system may be of value is estimating metabolic cost. Studies have found that stance time is inversely related to metabolic cost of locomotion and empirical equations have been developed to predict metabolic cost from stance time (e.g., Kram and Taylor 1990; Hoyt and Weyand 1997). However, the results from the portable F-scan system showed that the relationship in its current form does not apply to nonlevel terrain. (The metabolic cost of running uphill should be greater than on level terrain but a decrease in stance time that corresponds to increased metabolic cost was not seen.) Unlike systems designed to only measure stance time, the portable F-scan system measures plantar loads and may provide additional information to more accurately calculate metabolic cost. Thus, the portable system has the potential to further our understanding of many issues by chronicling the load history for specific regions of the foot under a wide range of conditions.

Conclusions

The modification of the F-scan system allows plantar pressure readings outside the laboratory, permitting the analysis of novel movements that may aid in our understanding of many biomechanic problems such as overuse injuries. Further development of the portable system should enhance its value as a biomechanic tool. The current portable system was limited to approximately 4000 frames of data per foot and it may be desirable to increase the capacity of the system to include additional frames and/or the ability to pause the data collection. Either modification will extend the amount of time the system can collect data, an important requirement in the study of overuse injuries. Pre-processing before saving to the memory system would also increase the data collection time by saving

data more efficiently (e.g., summing TekUnits in specific foot regions). However, important information may be lost. In addition, although the portable system is relatively small and lightweight, a further reduction in size and mass would be beneficial by reducing the impact the sensor has on the movement of a subject. This could be accomplished by using batteries that are more advanced as well as redesigning the interface between the sensor and the portable system.

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